# Proton Induced Recoil Trajectories and The Angular Dependence of Single-Event Upset Cross-Section Measurements

**R.A. Reed[1], P.W. Marshall[2], H. Kim[3], P.J. McNulty[4], B. Fodness[5], T. Jordan[2], R. Reedy[6], C. Tabbert[6], S.T. Liu[7], W. Heikkila[7], S. Buchner[8], K. LaBel[1]**

1. NASA/GSFC
2. Private Consultant
3. J&T/GSFC
4. Clemson University
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# Background

- **Proton induced recoil trajectories are historically considered to be a 2nd order effect in most microelectronic devices**
  - **Most proton-induced Single Event Upset (SEU) testing is carried out with the proton beam normal to the die surface**
- **In 1994 and 1995 Reed, et al. presented proton-induced SEU simulation results that predicted an angular dependence if:**
  - **The sensitive volume had at least one dimension sufficiently thin compared to the others, and**
  - **Critical charge was sufficiently large**
- **Very limited data available that shows an angular effect**
  - **Proton data presented by Gardic et al, at RADECS in 1995 showed angular effect data on a Silicon-On-Insulator (vendor unnamed) and a Matra (HM65656) Bulk CMOS memory devices**
  - **In 1997, we presented proton data at NSREC on the bulk device from Matra (HM65656). Our data did not show an angular effect.**

# Outline

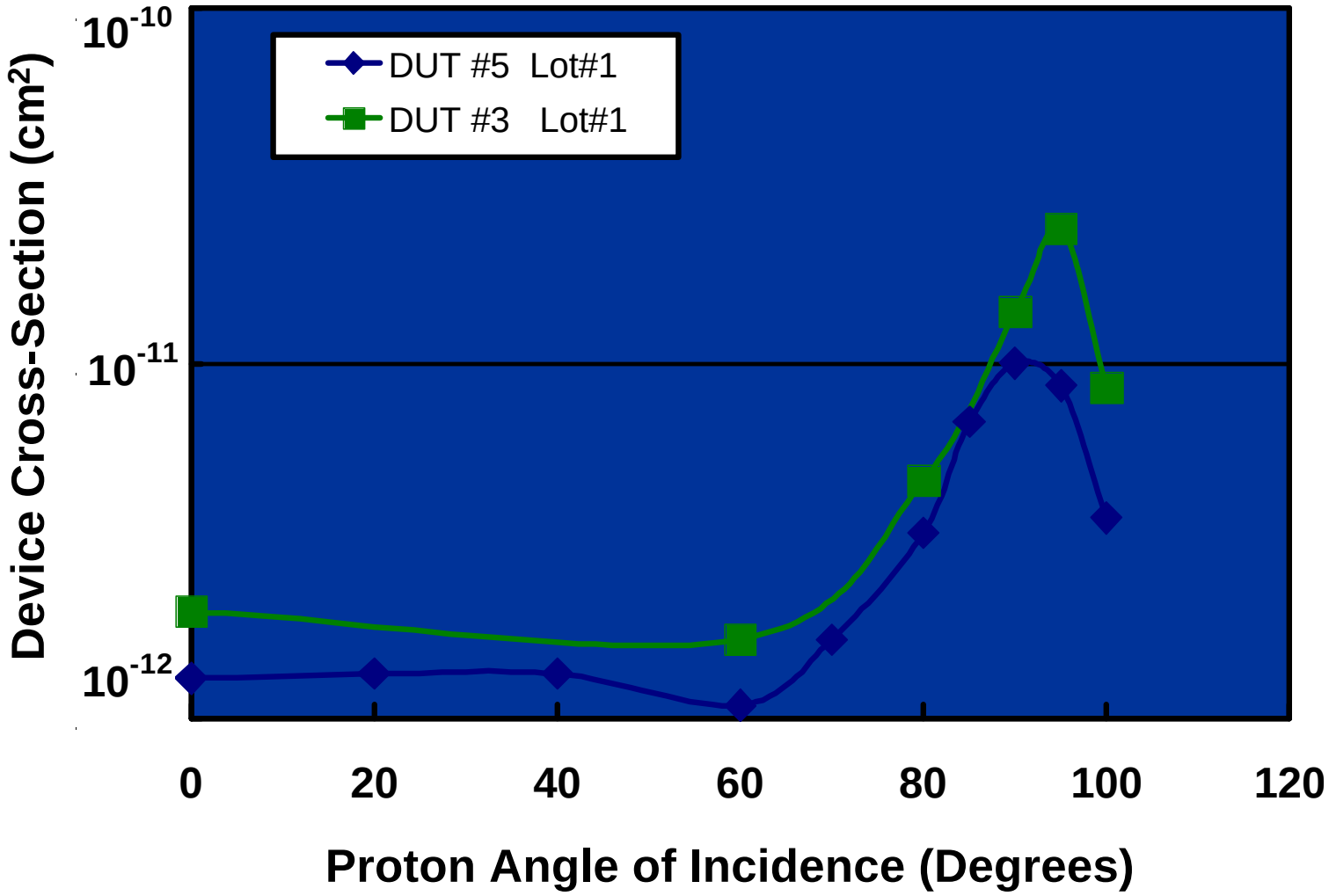
- **Proton-induced SEUs over proton beam angle-of-incidence**
  - **Experimentally determine if an angular effect exists**
  - **Investigate the relationship between proton energy, critical charge and the angular effect.**
- **Proton interaction effects on recoil trajectories and charge deposition in thin structures**
  - **Review and discuss the basic p+Silicon interaction mechanisms and determine how each induces an angular effect**
- **Modeling the Effects of Proton Beam Angle-of-Incidence**
  - **Compare experimental results to new simulation on test devices that are based on actual device geometries**
- **Conclusions**

# Devices Tested and Test Organizations

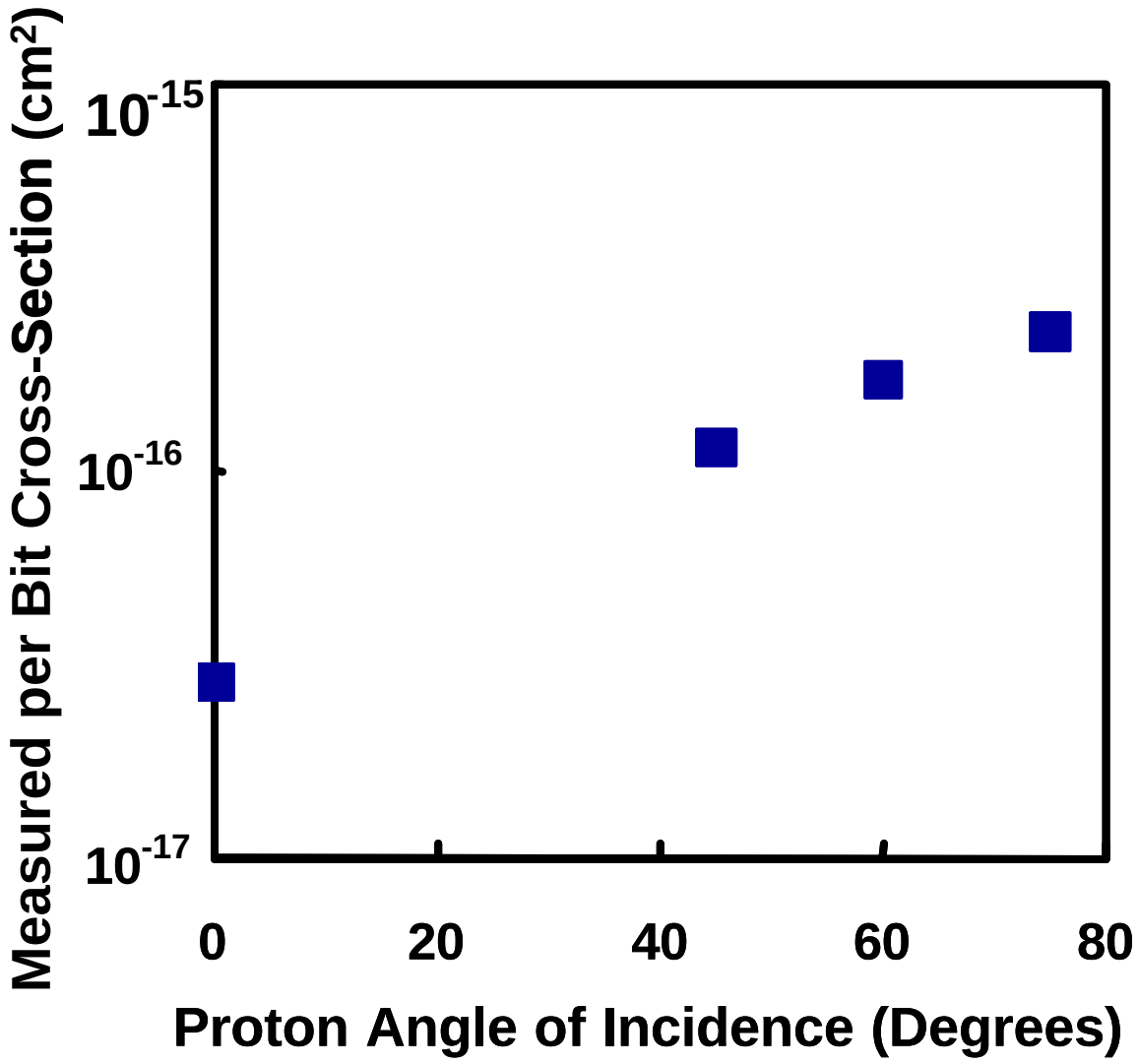
- **Peregrine Semiconductor 3.5 GHz Prescaler**
  - 0.5 ?m Ultra Thin Silicon (UTSi.™) Silicon-On-Sapphire (SOS) Process
  - Gate Length = 0.5 ?m and Width = 1.5 ?m to 10 ?m
  - Thickness of Silicon under gate = 0.098 ?m
  - Testing performed by NASA Goddard Space Flight Center
  - Testing performed at University of California at Davis and Indiana University

- **Honeywell 512K x 8 Static RAM**
  - 0.35 ?m RICMOS™ V Silicon-On-Insulator (SOI) Process
  - Gate Length = 0.35 ?m and Width = 1 ?m
  - Thickness of Silicon under gate = 0.21 ?m
  - Testing performed by Honeywell SSEC
  - Testing performed at Indiana University

# 63 MeV Proton Bit Error Events
# Peregrine Prescaler



# 158 MeV Proton-Induced Upsets in Honeywell 4M SRAM



# Very Different Circuits Show an Angular Effect

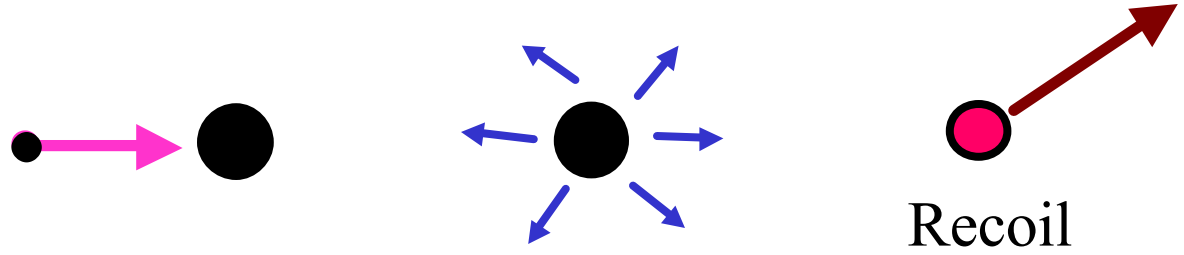
- Experimental data shows sensitivity of SOI and SOS technologies to proton beam angle-of-incidence
- Two very different circuits and test conditions
  - The Honeywell device is a SRAM tested in static mode
  - Peregrine device is a high speed prescaler with inputs set at 3.5 GHz
  - Angular effect is not a circuit phenomena
- Both technologies have sensitive volumes with large aspect ratios (max length / min length)
  - Peregrine is up to 100
  - Honeywell is up to 5

- **What is the basic mechanism that causes the angular effect?**

# Proton-Induced Direct Ionization

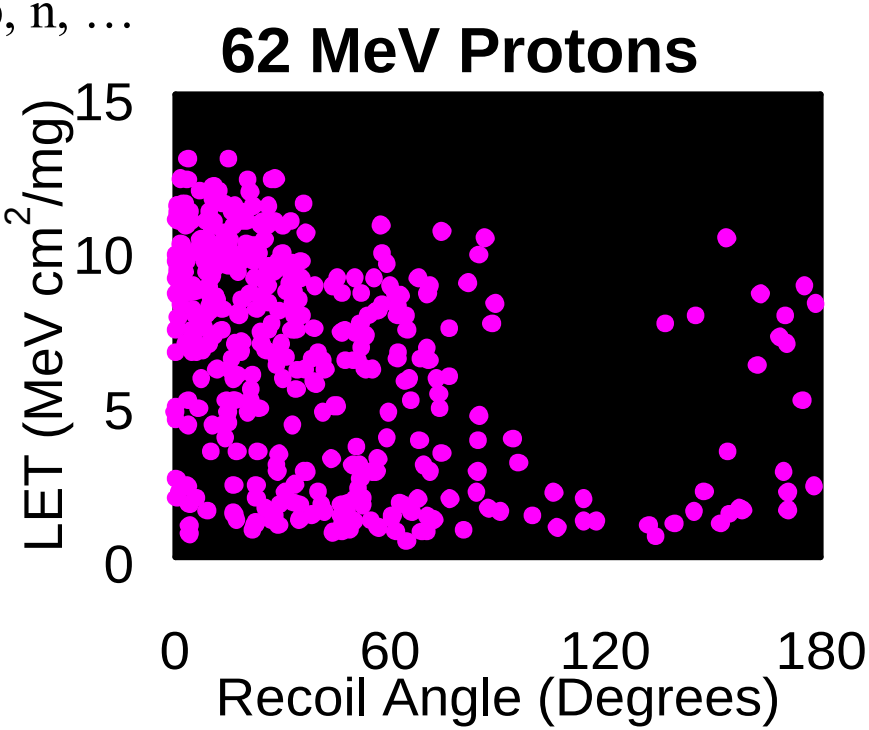
- **Direct ionization: primary proton interacts with electrons of the Silicon atom to liberate charge**
- **Can direction ionization cause the effect for the Peregrine prescaler?**
  - **Heavy ion threshold LET is ~ 2.5 MeV • cm$^2$/mg**
  - **To upset the prescaler, 63 MeV proton must have a path through a sensitive volume that is > 30 ?m**
  - **Maximum path length is ~10 ?m**
- **Honeywell SRAM?**
  - **158 MeV proton must have a path through a sensitive volume that is > 150 ?m**
  - **Maximum path length is ~1 ?m**
- **Direction ionization cannot induce an upset in these devices at the test energies used for this study**

# Inelastic Scattering with Target Nucleus



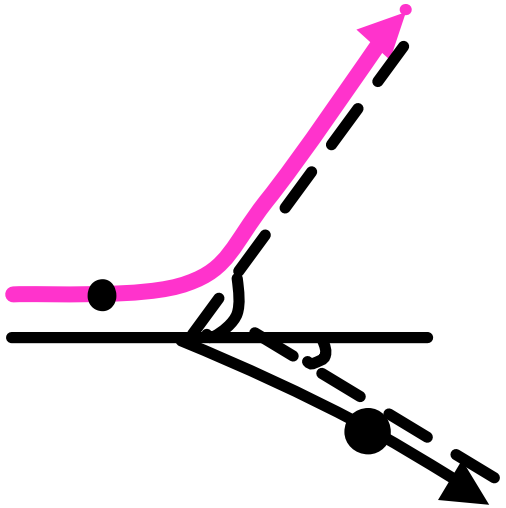

## Modeling the interaction

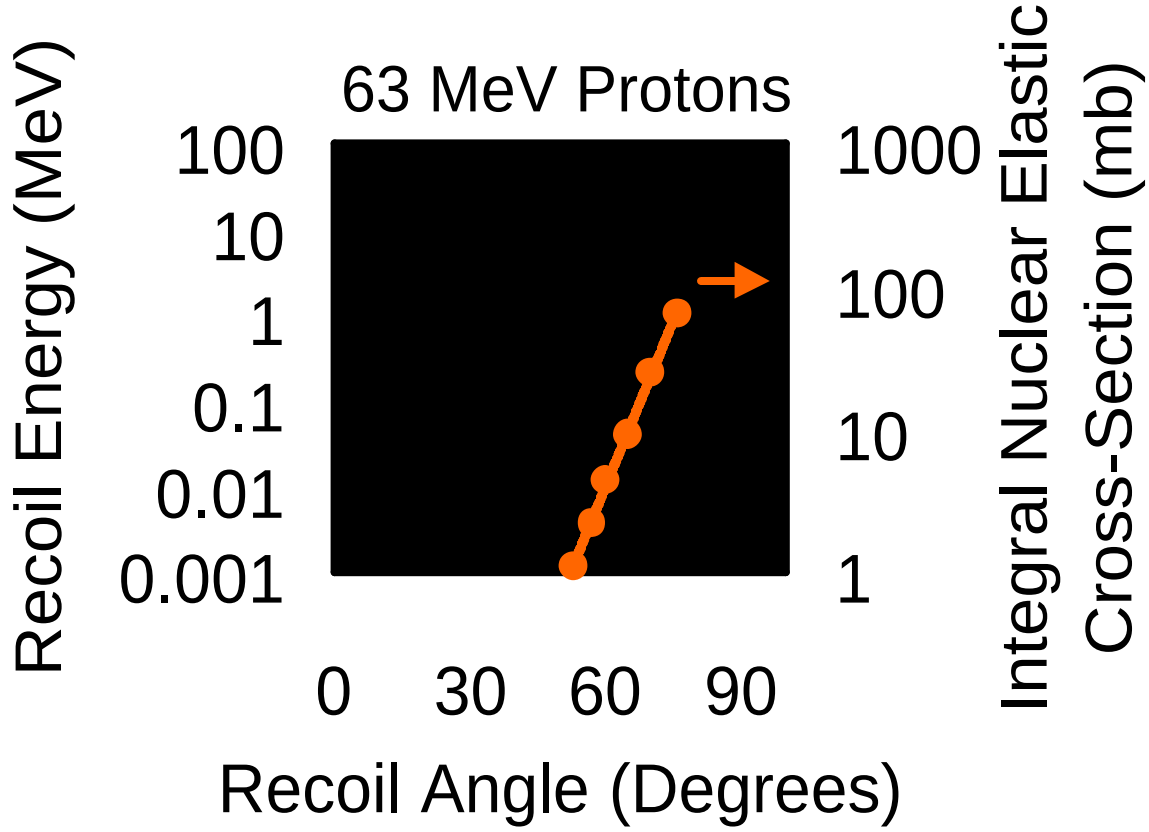
- **GEANT is a Monte Carlo modeling tool that can simulate spallation reactions**
- **Use GEANT to Model recoil angle**



# Elastic Scattering with Target Nucleus

**Assume billiard ball collision physics to model interaction**





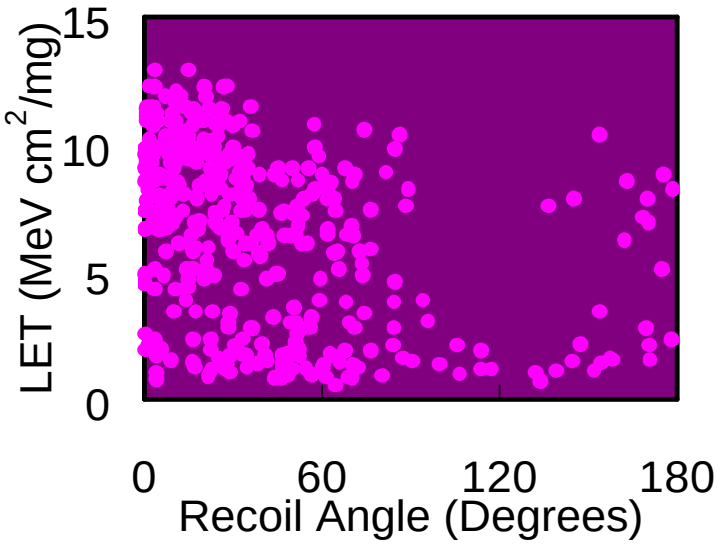
# Comparing Nuclear Interactions

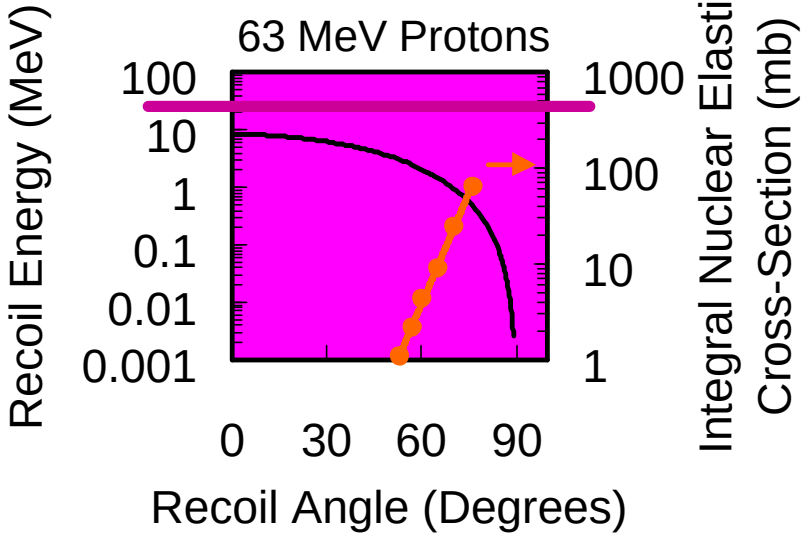
## Which one dominates?

- Nuclear Inelastic cross section is >350 mb
- Inelastic cross section is more that a factor of 4 greater than elastic
- Forward directed recoils are dominated by inelastic
- Inelastic's dominate Energies > 63 MeV

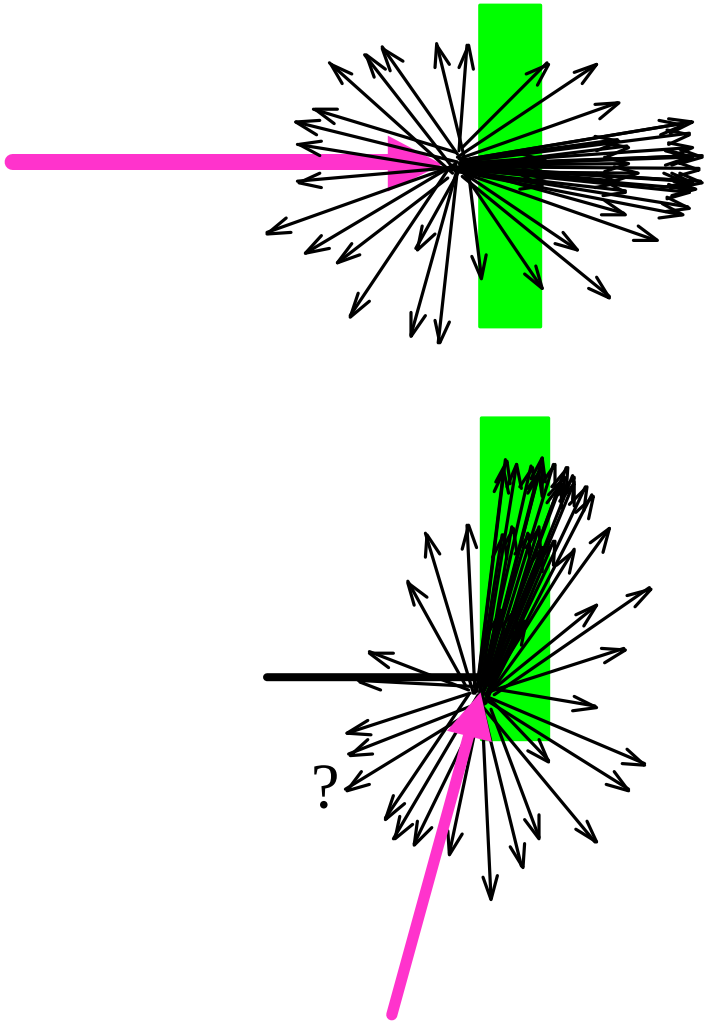
## Not a general result

- Elastic cross section peak at 30 MeV
- Elastics may become important at 30 MeV



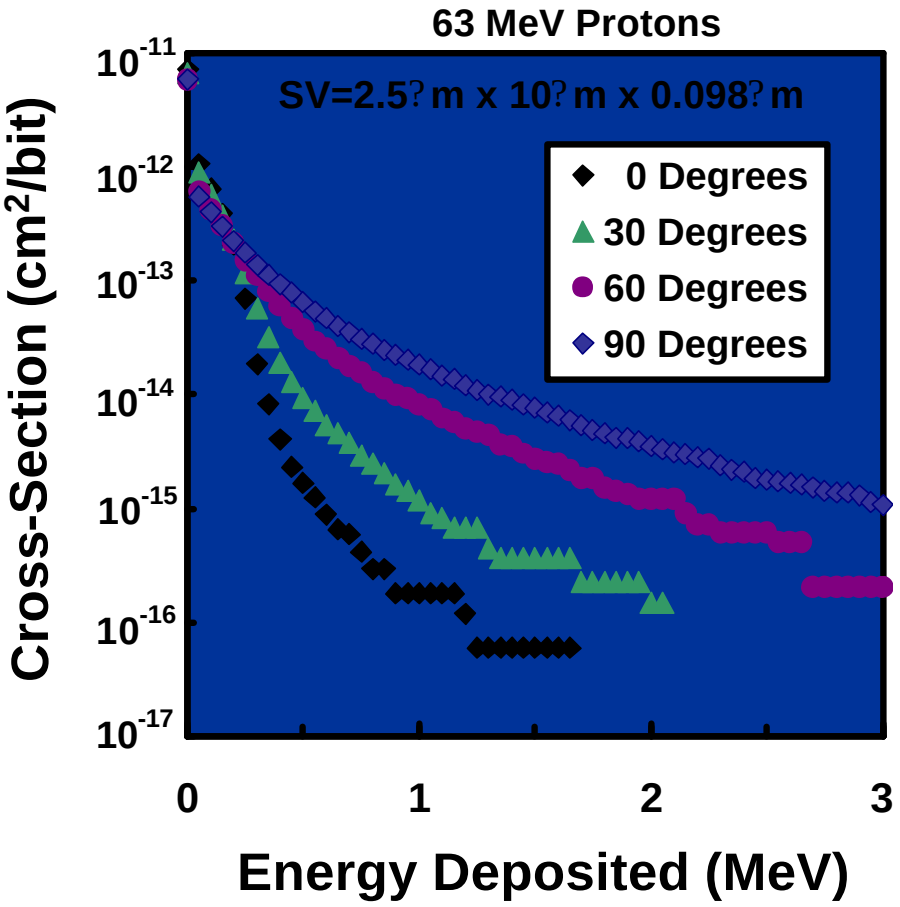
# Data Trends are Consistent with Spallation Reaction




- **Path length <u>increases</u> as incident proton angle <u>increases</u>**
- **More energy is deposited in sensitive volume at grazing angles**
- **This is consistent with the data on SOI and SOS devices**

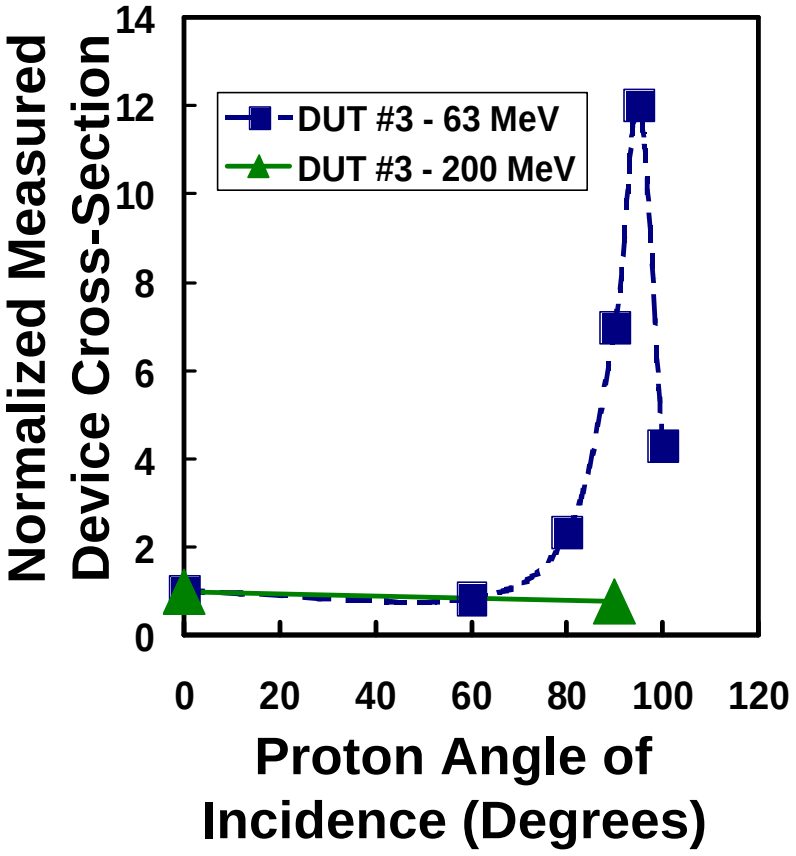
# Modeling Energy Deposition from Spallation Reactions

- Clemson University Proton Interactions in Devices (CUPID)
- Monte Carlo simulation codes for spallation reaction
- Predicts the integral cross section for depositing energy in a sensitive volume (SV)
- Input parameters include
  - Proton energy
  - Proton incident angle
  - SV dimensions
  - Surrounding volume dimensions

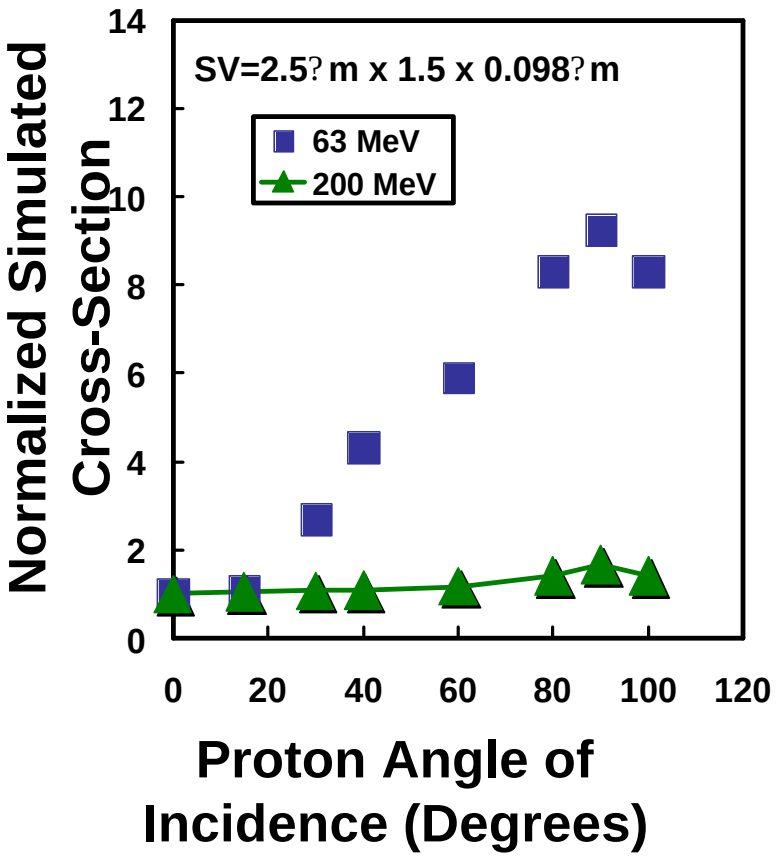


# Experimental Data and Modeling Results for Peregrine SOS Technology - Energy Dependence

## Measured Data



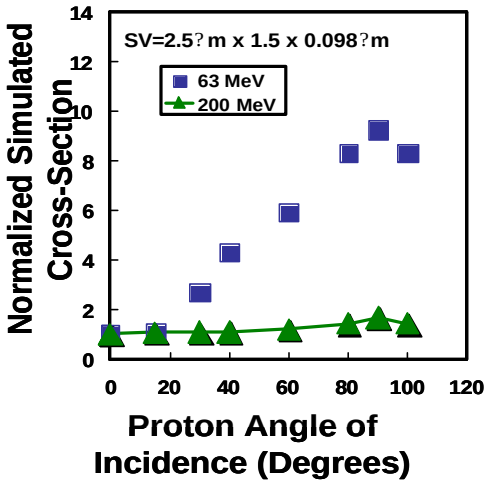

## Simulations



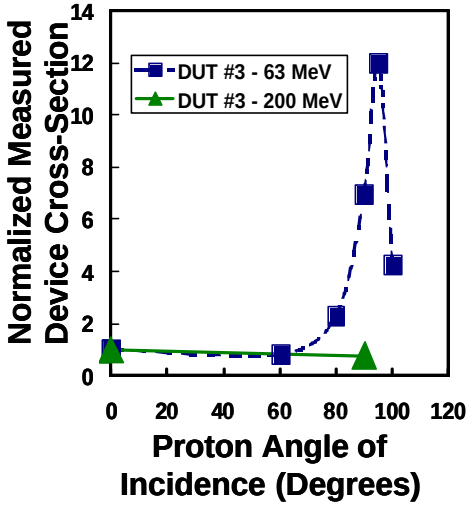
# Experimental Data and Modeling Results for Peregrine SOS Technology - Energy Dependence

- **Magnitude of angular effect depends on incident proton energy**
  - **Spallation products from 200 MeV p+Si inelastic collisions are more isotropic for LETs < 6**
- **Simulations agree with well with measured data near 0 and 90 degrees**
- **Contribution from elements other then Silicon can explain the disagreement between 30 and 60**
  - **GEANT simulations**

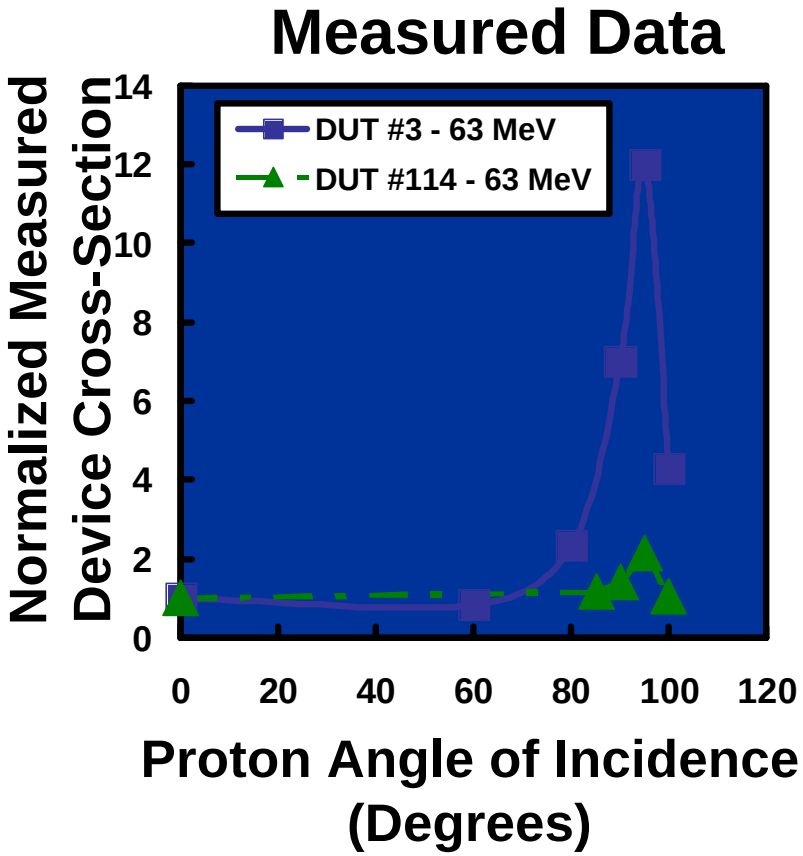
**Simulations**




**Measured Data**



# Experimental Data for Peregrine SOS Technology - Critical Charge Dependence




**Device #3 has a 50% higher threshold LET**

# Conclusions

- New proton SEU data demonstrate enhanced sensitivity in SOI technologies, including SOS
  - Classical testing approach would under predict on-orbit SEU rate
  - This effect is not limited to SOI technologies. Any device with an aspect ratio >3 and a critical charge >20 fC is suspect
- Spallation reaction is the dominate mechanism for the devices tested, elastics may be important at 30 MeV
- Experimental data showed angular effect can depend on proton energy and critical charge
- New simulations result show “good” agreement with experiments over energy and critical charge
- Our findings impact both test planning and rate prediction approaches, and present methods may underestimate observed upset rates by > 5x